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Nuclear Resonance Absorption as a Diagnostic and Investigative Technique

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ABSTRACT

This report reviews the process of resonance absorption of electromagnetic radiation by nuclei of a given species whose atoms comprise part or all of a solid material. The absorption process results in having nuclei in a short-lived excited state which may have several modes of decay. We pay special attention to the case where there exists a long-lived state between the excited state and the ground state of the nucleus; and where a significant fraction of the decays of the excited state populate this long-lived state, and where the latter state then decays predominantly by the emission of an observable gamma ray. We suggest the use of this process, i.e., of absorption and delayed re-emission of electromagnetic radiation, as a diagnostic tool to aid in obtaining the energy spectrum of a source of pulsed radiation, where the pulse duration is short compared to the lifetime of the intermediate state. With the general characteristics of the GAMBLE I facility at the Naval Research Laboratory in mind, we have carried out a survey of nuclear compilations in a search for stable nuclei having the desired three-level structure described above.

Three possible examples are given. Of these, ^{77}Se was selected as a candidate for demonstrating the feasibility of the technique. In a test, a specially fabricated disk of elemental selenium was exposed to a burst of radiation at the GAMBLE I facility and then examined with a scintillation detector. The experiment was successful in detecting the 18.1-sec activity of the 161-keV state in ^{77}Se, thus demonstrating the feasibility of the approach. It is suggested that the procedure can be reversed; i.e., if the spectrum of a radiation device is known, the device can be used as a research tool to search for new isomeric states or to measure as yet undetermined nuclear parameters of known states.

PROBLEM STATUS

This is a final report on one phase of a continuing problem.

AUTHORIZATION

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NUCLEAR RESONANCE ABSORPTION AS A DIAGNOSTIC AND INVESTIGATIVE TECHNIQUE

INTRODUCTION

Short-wavelength electromagnetic radiation, in passing through matter, interacts strongly with the electrons and, in many cases, also with the nuclei of the constituent atoms. One of the ways in which such radiation interacts with nuclei is through resonance absorption. This process can occur when an impinging photon has an energy equal to the sum of the energy of a specific nuclear level plus the kinetic energy of the recoiling nucleus. When resonance absorption occurs, the nucleus undergoes a transition from the ground state to a specific excited state. The excited state can then de-excite in one of several possible ways. For example, it may undergo a radiative transition directly to the ground state by emitting a single photon with an energy equal to the excitation energy minus the recoil energy of the nucleus. It may also undergo two or more successive radiative transitions and thereby reach the ground state by emitting two or more photons. In this case, the sum of the energies of the photons equals the excitation energy with a correction for nuclear recoils. In many cases, conversion electrons may also be emitted. If all the relevant transition probabilities of the nucleus are well known, the detection of the emitted radiation may be used to determine the intensity of the impinging radiation; conversely, if the spectrum of the incident radiation is known, one may be able to measure nuclear parameters characterizing the level excited in the absorption process.

THEORETICAL CONSIDERATIONS

The Absorption Process for a Stationary Nucleus

Consider a stable nucleus of mass M and spin I characterized by a spectrum of many excited energy levels. For the moment, let us concentrate our attention on two of these states and the ground state as shown in Fig. 1. Let us designate the upper and lower excited states by E_2 and E_1 (their respective energies above the ground state) and their mean lifetimes by τ_2 and τ_1, respectively.

The spin of state E_2 is given by J_2. Because an excited state decays exponentially with time, its energy is not sharply defined but is characterized by an energy spread or width Γ. If Γ is taken as the full width at half-maximum of the energy profile of a state, it may be shown by a simple Fourier transformation that Γ is related to the mean lifetime τ of that state by the equation

$$\Gamma \tau \approx \hbar = 6.58 \times 10^{-16} \text{ electron volt-seconds} . \quad (1)$$

Thus the two excited states have full widths at half-maximum given by Γ_2 and Γ_1, respectively. Since each state may have several modes of decay, not all shown in Fig. 1, each mode can be assigned a partial width. Then Γ_2 and Γ_1 are the sums of such partial widths. Thus

$$\Gamma_2 = \Gamma^{\gamma}_{2,0} + \Gamma^{\gamma}_{2,1} + \cdots$$
$$\Gamma_1 = \Gamma^{\gamma}_{1,0} + \cdots , \tag{2}$$

where the symbol $\Gamma^{\gamma}_{i,j}$ is the partial width for the transition from state E_i to the state E_j accompanied by the emission of a photon of energy $E_i - E_j - E_R$, where E_R is the kinetic energy of the recoiling nucleus.

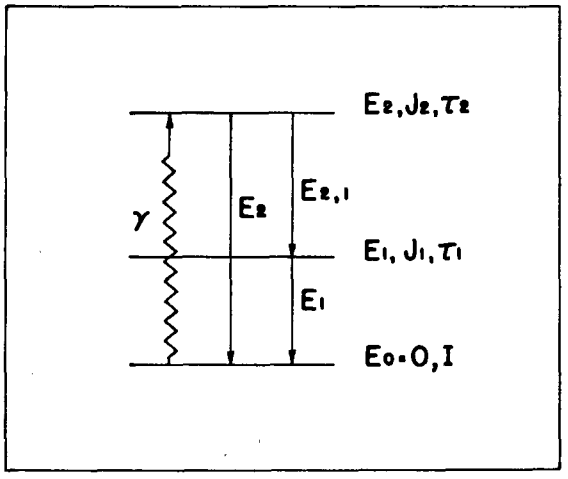

Fig. 1 - A nuclear three-level diagram: the state E_2 is formed in the absorption process, and the state E_1 is observed in the decay process.

Consider a photon interacting with the above nucleus and having an energy E_γ very close to E_2 plus the nuclear recoil energy ($E_\gamma^2/2Mc^2$) (i.e., within an energy interval of the order of Γ_2). The photon then has a probability for being absorbed by exciting the nucleus to the state E_2. The cross section for this process is given by (1)

$$\sigma_{abs}(E) = \left[4\pi \lambda\!\!\!^{-2} \frac{\Gamma^{\gamma}_{2,0}}{\Gamma_2} \frac{2J_2 + 1}{2(2I+1)} \right] \frac{1}{1 + x^2} , \tag{3}$$

where

$\lambda\!\!\!^{-} = \frac{1}{2\pi}$ times the wavelength of radiation of energy $E = \frac{hc}{2\pi E}$

$x = (E - E_2)/(\Gamma_2/2)$

$$E = E_\gamma - \frac{E_\gamma^2}{2Mc^2} .$$

At resonance, i.e., at $x = 0$ (or $E = E_2$),

$$\sigma(x=0) = \sigma_0 = 4\pi \lambda\!\!\!^{-2}_{x=0} \frac{\Gamma^{\gamma}_{2,0}}{\Gamma_2} \frac{2J_2 + 1}{2(2I+1)} . \tag{3a}$$

In Eq. (3), the quantity in the brackets varies very slowly compared to the resonance factor $1/(1+x^2)$. Thus, throughout the energy region of interest the bracketed quantity can be considered as a constant equal to the peak value σ_0; we can therefore rewrite Eq. (3) as

$$\sigma_{abs}(E) = \sigma_0 \frac{1}{1+x^2} . \tag{3b}$$

The probability for the state E_2 to decay to the ground state by the emission of a single photon of energy close to E_2 is simply the branching ratio $\Gamma^{\gamma}_{2,0}/\Gamma_2$. This "resonant" scattering process therefore has the cross section

$$\sigma_{scatt}(E) = \frac{\Gamma^{\gamma}_{2,0}}{\Gamma_2} \sigma_{abs}(E)$$

$$= \frac{\Gamma^{\gamma}_{2,0}}{\Gamma_2} \sigma_0 \frac{1}{1+x^2} , \tag{4}$$

and this is the cross section which applies if the absorption process is to be observed by detecting the photon with the full energy E_2.

The state E_2 also has a probability for decaying to the state E_1 by an electromagnetic transition. This probability is given by the branching ratio

$$\frac{\Gamma_{2,1}(\text{electromagnetic})}{\Gamma_2} = \frac{\Gamma^{\gamma}_{2,1} + \Gamma^{i.c.}_{2,1}}{\Gamma_2} = \frac{(1+\alpha_{2,1})\Gamma^{\gamma}_{2,1}}{\Gamma_2} ,$$

where

$\Gamma^{i.c.}_{2,1}$ = the partial width for the transition $E_2 \rightarrow E_1$ by an internal conversion process

$\alpha_{2,1}$ = internal conversion coefficient for this process.

The state E_1 then has a probability for decaying to the ground state through the emission of a gamma ray of energy E_1. This probability is given by the ratio $\Gamma^{\gamma}_{1,0}/\Gamma_1$. Thus if the absorption process is to be observed by detecting photons of energy E_1, the cross section that applies is given by the expression

$$\sigma_{E1}(E) = \frac{\Gamma^{\gamma}_{1,0}}{\Gamma_1} \frac{(1+\alpha_{2,1})\Gamma^{\gamma}_{2,1}}{\Gamma_2} \sigma_{abs}(E) . \tag{5}$$

As we shall see, in cases where the intermediate state is relatively long-lived, it will be advantageous to observe the transition $E_1 \rightarrow E_0$; for, in such cases, the target containing the absorbing nuclei can be observed well after the direct effects of the pulse of radiation have passed away.

The Absorption Process for the Nucleus Bound in a Solid Target

The expressions given above are for an idealized situation which in reality never obtains. In an actual experiment, nuclei are not stationary but are in thermal motion.

By virtue of the Doppler effect, radiation incident on a moving nucleus is shifted in energy relative to that nucleus. The overall effect of all such shifts is to broaden the natural width Γ_2 and to change the shape of the resonance. Therefore, taking Doppler broadening into account, Eq. (3) is modified as follows (2):

$$\sigma_{abs}(E) = \sigma_0 \, \psi(\xi, x) \ . \tag{6}$$

As expected, for stationary nuclei the function $\psi(\xi, x)$ has the limiting value given by

$$\psi(\xi, x) \longrightarrow \frac{1}{1 + x^2} \ , \tag{7}$$

where x has the same meaning as before. For real nuclei embedded in a solid, the function $\psi(\xi, x)$ is given by the equation (3)

$$\psi(\xi, x) = \frac{\xi}{2\sqrt{\pi}} \int_{-\infty}^{+\infty} \frac{1}{1 + y^2} \, e^{-\xi^2 (x-y)^2/4} \, dy \ . \tag{8}$$

The integration variable y is defined as $y = (E' - E_2)/(\Gamma_2/2)$, where E' = the Doppler shifted energy. The parameter $\xi = \Gamma_2/\Delta$, where Δ is the Doppler width and is given by the expression

$$\Delta = E_2 \sqrt{\frac{2k\,T_{eff}}{Mc^2}} \tag{9}$$

for the case

$$(\Gamma_2 + \Delta) >> 2k\,\Theta \ . \tag{10}$$

In the above expression,

Θ = Debye temperature of the solid,

k = Boltzmann constant,

M = mass of the nucleus.

To go from the laboratory temperature T to the effective temperature T_{eff}, one uses the expression

$$T_{eff} = T\left[\frac{C_v(\Theta/T)}{24} + \frac{3(\Theta/T)}{4(e^{\Theta/T} - 1)} + \frac{3(\Theta/T)}{8}\right] , \tag{11}$$

where C_v is the specific heat function. This function has been tabulated (4). In the cases that we shall consider, not only is the condition required by Eq. (10) met, but, in addition, $\Delta >> \Gamma_2$, i.e., $\xi << 1$. In this limit,

$$\psi(\xi, x) \longrightarrow \frac{\sqrt{\pi}}{2} \xi \, e^{-\xi^2 x^2/4} \ , \tag{12}$$

and Eq. (6) becomes

$$\sigma_{abs}(E) = \frac{\sqrt{\pi}}{2}\,\xi\,\sigma_0\,e^{-\xi^2x^2/4} = \sigma_0'\,e^{-\xi^2x^2/4}\ , \tag{13}$$

where $\sigma_0' = (\sqrt{\pi}/2)\ \xi\ \sigma_0$ is now the effective peak cross section. Thus, as indicated in Fig. 2, because of thermal motion, the resonance is broadened from an intrinsic Breit-Wigner shape with a full width at half-maximum of Γ_2 to a Gaussian shape with a full width at e^{-1} times maximum of 2Δ. The peak cross section is reduced by a comparable factor, and the area under the resonance curve remains unchanged and equal to $(\pi/2)\sigma_0\Gamma_2$.

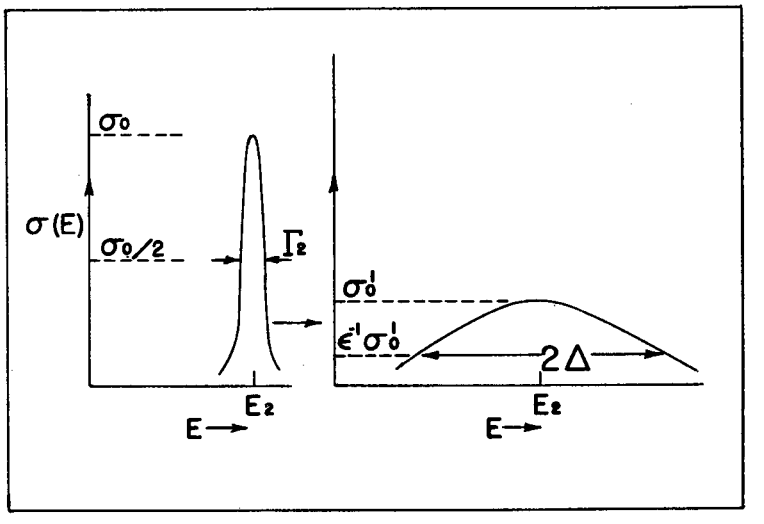

Fig. 2 - The energy profiles of the natural resonance (left) and the Doppler broadened resonance (right)

General Considerations for the Measuring Process

Let us assume that we have a single intense burst of radiation with a time duration T, and with a continuous energy spectrum ranging from $E_{min} \geq 0$ to E_{max}; and that at several points in the spectrum, we wish to measure N(E), the number of photons per unit energy at the energy E. In determining the spectrum, the small energy difference between E and E_γ is insignificant; for example, for a 0.50-MeV photon interacting with a mass-50 nucleus, the difference $(E - E_\gamma)$ is about 2.5 eV. Let us assume that we have at least one naturally occurring element such that it or one of its compounds can be fabricated into a disk; and that the element has an isotope with the following nuclear properties:

1. The nucleus is stable.
2. The relevant nuclear transition probabilities are known.
3. Two of its excited states conform to the diagram of Fig. 1.
4. The upper level E_2 falls within the range $E_{min} < E_2 < E_{max}$.
5. $\tau_1 >> \tau_2$.

Let us assume also, for simplicity, that the disk will be held near the source of radiation; and that, after the radiation burst, the disk will be examined for radioactivity by a detector such as a large NaI(Tl) scintillator mounted on a multiplier phototube; and that the pulses from the detector will be fed into electronic circuitry including a multichannel pulse-height analyzer. As we have seen, we have the choice of detecting radiation either of energy E_2 from the excited state or of energy E_1 from the intermediate state. In either case, during a given counting interval the detection system will yield a total number of counts of detected photons of that energy. Ignoring electronic absorption processes in the disk, from the detector geometry and efficiency and from the lifetime of the observed state, one calculates the total number of radioactive nuclei N_0 produced in the disk by the burst. The number N_0 will be proportional to $N(E_2)$, the intensity of radiation in the burst at the energy E_2.

For a target of thickness d, subtending a solid angle Ω at a point source of isotropic radiation and with the assumption that a plane wave of radiation is incident on that target, we have the following relationship between N_0 and $N(E_2)$:

$$N_0 = N(E_2) \frac{\Omega}{4\pi} \int_0^\infty \frac{\sigma}{\sigma'_e + \sigma} \left\{1 - \exp\left[-(\sigma'_e + \sigma) nd\right]\right\} dE \ , \tag{14}$$

where σ is given by either Eq. (4) or Eq. (5), depending upon which radiation has been selected for observation; n is the number of nuclei per cubic centimeter of the isotope we are using, and σ'_e is the total electronic absorption cross section per atom times the ratio n'/n where n' is the number of atoms per cubic centimeter. In principle then, depending upon the sensitivity of the experiment, a determination of N_0 yields the desired value for $N(E_2)$.

The questions to be resolved include the selection of target nuclei, the choice of the radiation to be detected, and the determination of the target thicknesses to be used. Here, considerations of lifetimes and cross sections are of great importance. If we wish to measure in situ, initiating a counting interval shortly after the burst is over, we must shield the scintillator from the direct burst. Even so, trial calculations show that with targets several millimeters thick and with $E_{max} \leq 1$ MeV, Compton scattering processes in the target, due to incident radiation of all energies, would deposit a sufficient amount of energy in the NaI(Tl) scintillator (for a detector at 90° to the incident radiation) to render it useless for several microseconds, if we assume it to be undamaged during the burst. Initially, then, let us consider a lifetime $\tau \gg 1\ \mu$sec for the state whose decay is being observed. Assume for the moment that we are observing the direct decay of the excited state E_2 and that $\tau_2 \approx 10\ \mu$sec. Then according to Eq. (1), $\Gamma_2 \approx 5 \times 10^{-11}$ eV. In the energy range that we are considering, we shall find doppler widths with values of $\Delta \leq 0.5$ eV, yielding a value for ξ of $\approx 10^{-10}$. If $E_2 \approx 0.5$ MeV, Eq. (3a) tells us that $\sigma_0 \approx \lambda^2 \approx 10^4$ barns. According to Eq. (13), thermal motion attenuates this peak to an effective peak cross section of $\sigma'_0 \approx \xi \times \sigma_0 \approx 10^{-6}$ barns. If there are no electronic absorption effects, the fraction of incident radiation absorbed at the peak of the resonance in a target of thickness d with n nuclei per cubic centimeter is $[1 - \exp(-n\sigma'_0 d)]$.

If one requires, say even 0.1% of the incident radiation to be absorbed in the peak, then $n\sigma'_0 d \approx 0.001$ and $d \approx 10^4$ cm. This result would tend to make extremely difficult, if not rule out completely, the detection of the gamma radiation accompanying the direct decay to the ground state of the state E_2. To achieve a larger effective cross section requires a much bigger ξ which, in turn, requires $\tau \ll 1\ \mu$sec. We thus appear to have the apparently contradictory requirements of a very short lifetime for the absorption process and a long lifetime for the detection process. A resolution of the problem is achieved by utilizing the intermediate state E_1 in the detection process. We then require a very short-lived state E_2 to produce a large effective cross section in the absorption

process, a large branching ratio $\Gamma^{\gamma}_{2,1}/\Gamma_2$ to populate the E_1 state strongly, and a long lifetime for the E_1 state as well as a large value for $\Gamma^{\gamma}_{1,0}/\Gamma_1$ to permit the observation of the transition $E_1 \rightarrow E_0$. In addition, if $\tau_1 >> 1$ μsec, the target may be moved to a remote station for counting, thereby obviating exposure of the detector to damaging radiation.

EXPERIMENTAL CONSIDERATIONS

The Search for Suitable Nuclei

We have made an extensive search for nuclei having the properties cited above. As source material we used the compilations of three separate groups, namely: NDS, LHP, and MSS (5-8), as well as a number of recent publications. Roughly, we limited ourselves to the energy region from above 100 keV to below 1 MeV. Frequently, we found likely candidates, but their lifetimes or branching ratios were not known well enough for present purposes. In other cases, there was disagreement on published values of these parameters. Knowledge is still increasing; and it is therefore quite likely that additional useful cases may arise, or that parameters presently unknown will be measured. At present, our three most likely candidates are selenium-77, arsenic-75, and erbium-167; their energy level diagrams are reproduced in Fig. 3 with the levels E_2 and E_1 strongly accentuated. Their relevant characteristics are presented in Table 1. Here, T_1 and T_2 are half-lives.

Table 1
Characteristics of Three Possible Nuclei

Nucleus	E_2 (keV)	I	J_2	T_2	E_1 (keV)	T_1	α_1	$\frac{\Gamma_{2,0}}{\Gamma_2}$	$\frac{\Gamma_{2,1}}{\Gamma_2}$	$\frac{\Gamma_{1,0}}{\Gamma_1}$	Abundance (%)	θ
^{77}Se	249	1/2	5/2	(9.4 ± 0.4) nsec	162	(18.1 ± 0.2) sec	0.96	0.615	0.385 ±0.017	1.00	8.3	90° (vitreous)
^{75}As	401	3/2	5/2	(1.67 ± 0.03) nsec	304	(16.4 ± 0.4) msec	0.057	0.14	0.0625	0.997	100	174° (AsBr)
^{167}Er	532	7/2	3/2	(15 ± 6) psec	208	(2.3 ± 0.2) sec	1.36	0.97	0.02	1.00	24.4	T_{eff} = 1.04 T*

*See Ref. 13.

An Experimental Feasibility Test Using ^{77}Se

Of the three nuclei, selenium appeared to be the simplest to use in a test, since the long lifetime of the state E_1 permits the use of relatively unsophisticated equipment. Chemically pure selenium pellets were therefore melted and poured into a disk mold. The resulting disk was then annealed to ensure that the selenium was in the vitreous state since the Debye temperature is known for this case. The disk was positioned near the source of radiation at the GAMBLE I facility; E_{max} was kept under 1 MeV. After a single burst, the disk was moved to a NaI(Tl) scintillation detector used in conjunction with a standard multichannel pulse-height analyzer. A counting interval of two 18-sec half-lives was initiated, and a pulse-height distribution was obtained. It displayed a photopeak at 162 keV as shown in Fig. 4. A second irradiation and counting cycle gave similar results. It can then be safely assumed that the 249-keV state was excited, that it decayed to the 162-keV state, and that the decay of the latter state was observed. Both runs yielded the counts needed for a statistically meaningful intensity determination at the energy of 249 keV.

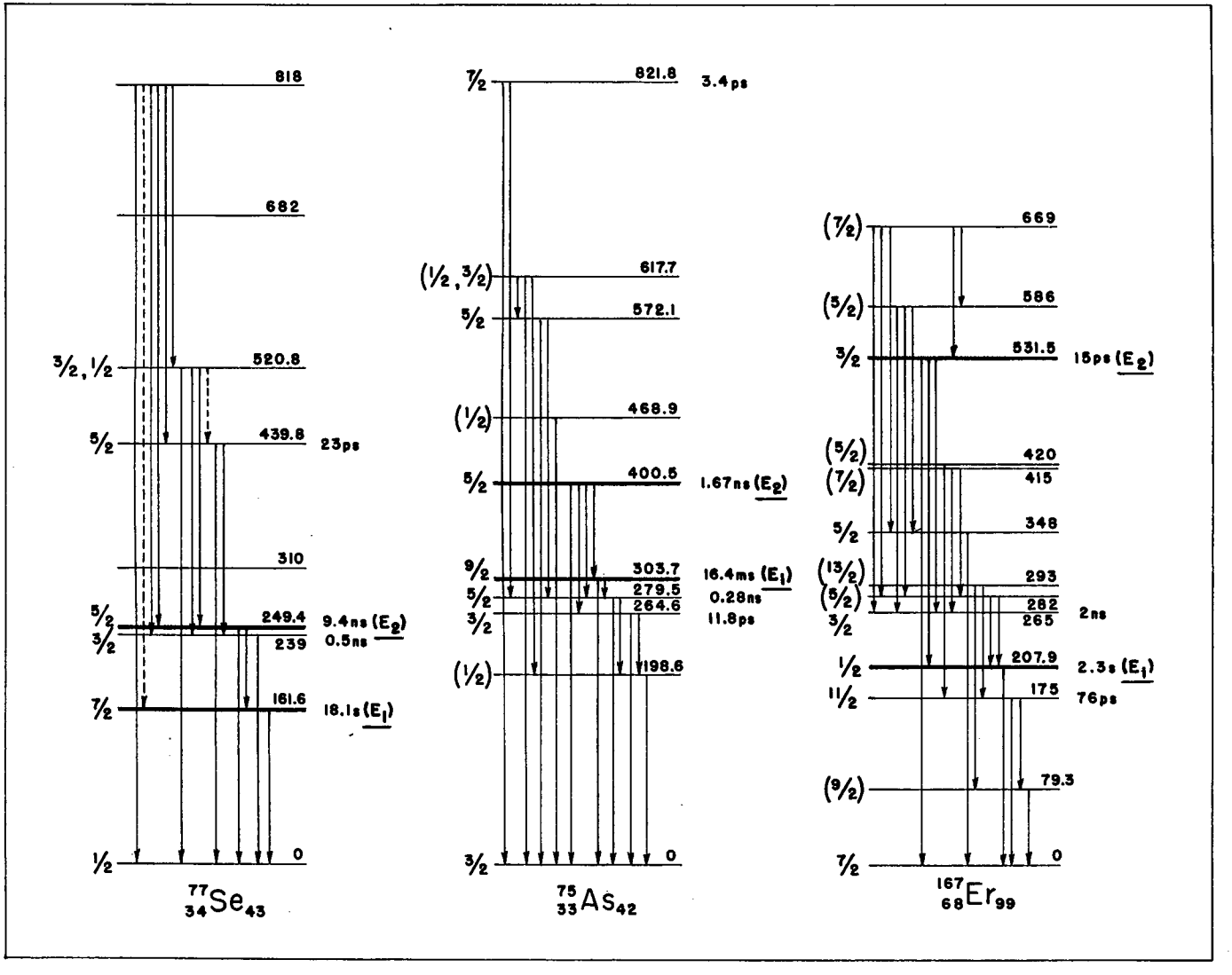

Fig. 3 - Energy level diagrams of the three nuclei ^{77}Se, ^{75}As, ^{167}Er. The states E_2 and E_1 are heavily accentuated. Known transitions are indicated by arrows, and known spins and half-lives are shown.

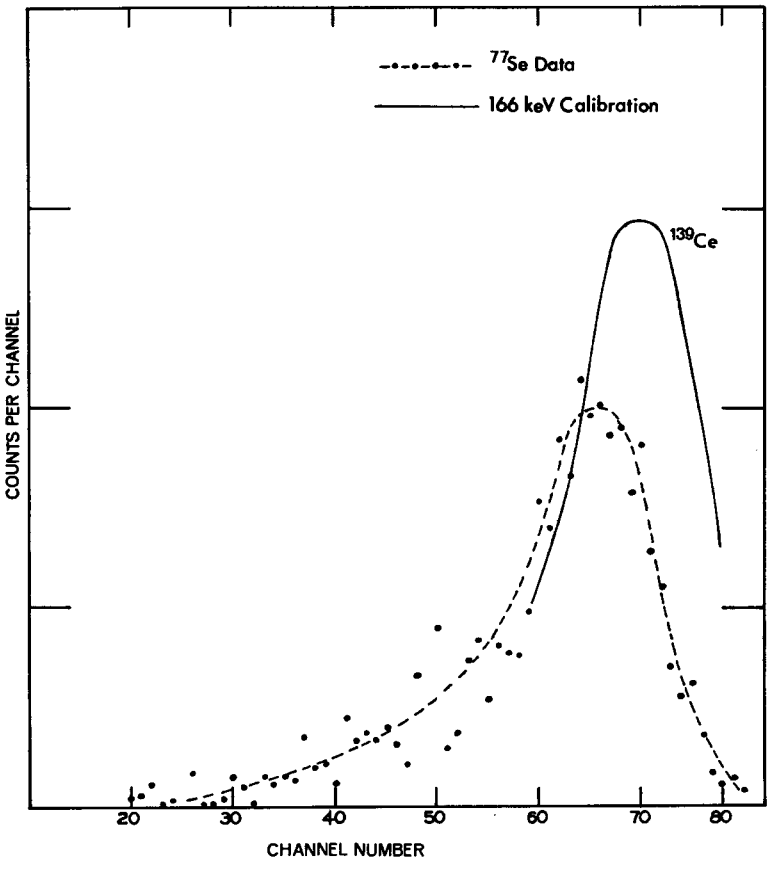

Fig. 4 - Pulse-height distributions. The solid line corresponds to a known gamma ray from a ^{139}Ce source, the dots represent data from an irradiated selenium disk, and the dashed line is drawn in to guide the eye.

However, one difficulty that must be taken into account for this nucleus is the existence of other states between E_2 and E_{max}. As is obvious from Fig. 3, if E_{max} were to exceed 521 keV, the 521-keV state would also be excited, and its decay would contribute to populating the 249-keV level. Therefore, if this effect were not taken into account, i.e., if the existence of the 521-keV state were ignored, an overestimate of the intensity at 249 keV would result. Although the spin of the 521-keV state is still uncertain, a rough estimate of the above contribution can be made. From the measured value of $B(E2)\uparrow = 0.010 \pm 0.002$ for this state (NDS (5, 6)), assuming that $J = 3/2$, we can calculate Γ^{γ}_{E2}, which is the width for the E2 part of the transition and is therefore a lower limit for Γ^{γ}_{521}. This calculation is carried out using the equation

$$\Gamma^{\gamma}_{E2} = 8.06\ E_{\gamma}^{5}\ \frac{B(E2)\uparrow}{\epsilon_{\gamma}}\ \frac{2I+1}{2J+1}\ \frac{\delta^2+1}{\delta^2}\ 10^{-3}\ \text{eV}\ , \tag{15}$$

where

E_{γ} = the energy in MeV of the excited state

I, J = the spins of the ground state and excited state, respectively

δ = the ratio $\frac{E2}{M1}$

ϵ_γ = the branching ratio for a radiative transition to the ground state through the emission of a single photon of energy E_γ.

We obtain the result $\Gamma_{521}/\Gamma_{249} \approx 30$ if we make the reasonable assumption that $\delta > 1$. With the aid of Eq. (3) we can also calculate $\sigma(521)/\sigma(249)$. It should now be noted from Eqs. (3) and (15) that in the product $\sigma\Gamma^\gamma_{E2}$, the quantity $(2J + 1)$ which is not well known does cancel out.

If we now assume a thin target and a flat spectrum, i.e., $N(E) = N(521) = N(249)$, the ratio of photons absorbed by the two levels would equal the ratio of the areas of the two resonances $= \sigma\Gamma(521)/\sigma\Gamma(249) \approx 8$. The 521-keV state has a 1.2% branching ratio for populating the 249-keV state. Therefore, the overestimate in the intensity for the above assumptions, if the existence of the 521-keV state were ignored, would be $\approx 10\%$. If, as we have done here, an approximate spectral shape can be assumed, the overestimate could be calculated with an uncertainty of better than 50%. The corrected intensity may then be in error by no more than about 5%.

It may also be possible to obtain the needed information experimentally by repeating the activation measurement at several energies, both above and below 521 keV, or by using the known thin-target bremsstrahlung from a low-energy electron accelerator. A more serious difficulty arises if $E_{max} > 680$ keV, for then another level which feeds the 249-keV state is excited. In this case however, none of the nuclear parameters is known; and, without additional information, no corrections could be made. This state of nuclear structure knowledge, even in ^{77}Se, is only one example of the continuing need for additional basic nuclear information. If we assume then that the contribution to the activity due only to direct excitation of the 249-keV level has been determined, there remains only a set of attenuation calculations to be made in order to obtain the desired intensity $N(249)$. For an isotropic source and a plane wavefront of radiation incident on the target, the activation of various layers of the disk, the attenuation of the 162-keV photons emanating from these layers, and the detection efficiency of various parts of the scintillator are needed. These calculations can be performed using tabulated absorption coefficients (9, 10). For a nonisotropic source or a spherical incident wave front, the distribution of activity in the disk is more complex, but the calculations would still be tractable. It might even be possible to do an approximate determination of the overall attenuation by activating the same target with the same source-disk geometry but utilizing a known bremsstrahlung spectrum from an electron Van de Graaff accelerator or linac. In principle, then, the intensity at one point in the spectrum would be determined, and intensities at other points might possibly be determined.

To summarize the above results, given an intense burst with $E_{max} \lesssim 0.5$ MeV, the intensity at 249 keV can be obtained provided that

1. The efficiency of the detector at 162 keV is known
2. Attenuation calculations can be performed for radiation entering the disk (E_2) and leaving (E_1)
3. All relevant nuclear parameters are known.

For cylinders of NaI, tabulations are available (11, 12) to take care of proviso 1. If a Ge(Li) detector is used, the efficiency can be obtained experimentally. Proviso 2 will require computer-assisted calculations that utilize cross sections for electronic and nuclear interactions and take into account the geometries of the disk and the detector.

For $E_{max} \leq 0.7$ MeV, the intensity can be obtained if an independent measurement helps to estimate the contribution from the 521-keV level.

It should be pointed out that the sensitivity can be improved by an order of magnitude over the present results by using a target that is highly enriched in ^{77}Se.

Other Nuclei

Arsenic-75 is 100% abundant and relatively inexpensive. Although only the bromide has a published Debye temperature, it may be assumed that of elemental arsenic is also low and that therefore $T_{eff} \approx T$. Table 1 gives the lifetime of state E_1 in milliseconds; a modification of the previous technique is therefore required. Counting would have to be done in situ by gating the electronics on for about 0.05 sec beginning several microseconds after the burst. One can detect both the 304-keV gamma ray listed in the table and the more abundant 280-keV gamma ray, which is part of the paralleling cascade, and thereby increase the sensitivity. The branching ratios are taken from NDS and are at some variance with LHP. There is also the question of possible contributions from higher levels whose characteristics are not known. At least a good estimate of the intensity at 0.4 MeV can be made if $E_{max} < 0.5$ MeV.

Erbium-167 is an isotope of a not readily available element. It may therefore have to be borrowed from Oak Ridge National Laboratory if an adequate amount is to be obtained. If it can be used to obtain an intensity measurement at 532 keV, the correction required for the contribution of the 521-keV level in ^{77}Se could be made. Again, characteristics of higher states of ^{167}Er are not known. Although a literature search did not reveal a Debye temperature for erbium, a correction is given in Table 1; it has been obtained from neutron absorption work (13). In the case of erbium, the absorption of E_2 and E_1 gamma rays in the first layers of the target disk is more serious because of the high Z. To detect the 2-sec lifetime, one can either count in situ or use a mechanical device such as a "rabbit" to move the disk rapidly to the detector.

Computed characteristics for the three nuclei are presented in Table 2. Of great importance are the extremely high peak cross sections which make resonance absorption so sensitive a process, and the very narrow widths of the isomeric states of energy E_1 which lead to negligible excitation of these states by direct absorption of gamma rays of energy E_1.

Table 2
Computed Parameters for the Three Target Nuclei

Nucleus	$\sigma(E_2)$ (barns)	Γ_2 (eV)	Γ_1 (eV)	Δ (eV)	ξ
^{77}Se	7.58×10^4	$[4.85 \pm 0.21] \times 10^{-8}$	2.5×10^{-17}	0.21	2.3×10^{-7}
^{75}As	1.07×10^4	$[2.85 \pm 0.05] \times 10^{-7}$	2.8×10^{-14}	0.34	8.3×10^{-7}
^{167}Er	2.41×10^4	$[3.04 \pm 0.18] \times 10^{-5}$	2.9×10^{-16}	0.31	9.8×10^{-6}

CONCLUSIONS

It has been successfully demonstrated in the case of ^{77}Se that resonant nuclear gamma-ray absorption can be used to make an intensity measurement for one point in the continuous spectrum resulting from a burst of x rays or gamma rays; and it has been

indicated that a variety of other nuclei are available for such measurements. It has also been pointed out that there is a need for additional basic nuclear physics studies.

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13. ABSTRACT

This report reviews the process of resonance absorption of electromagnetic radiation by nuclei of a given species whose atoms comprise part or all of a solid material. The absorption process results in having nuclei in a short-lived excited state which may have several modes of decay. We pay special attention to the case where there exists a long-lived state between the excited state and the ground state of the nucleus; and where a significant fraction of the decays of the excited state populate this long-lived state, and where the latter state then decays predominantly by the emission of an observable gamma ray. We suggest the use of this process, i.e., of absorption and delayed re-emission of electromagnetic radiation, as a diagnostic tool to aid in obtaining the energy spectrum of a source of pulsed radiation, where the pulse duration is short compared to the lifetime of the intermediate state. With the general characteristics of the GAMBLE I facility at the Naval Research Laboratory in mind, we have carried out a survey of nuclear compilations in a search for stable nuclei having the desired three-level structure described above. Three possible examples are given. Of these, ^{77}Se was selected as a candidate for demonstrating the feasibility of the technique. In a test, a specially fabricated disk of elemental selenium was exposed to a burst of radiation at the GAMBLE I facility and then examined with a scintillation detector. The experiment was successful in detecting the 18.1-sec activity of the 161-keV state in ^{77}Se, thus demonstrating the feasibility of the approach. It is suggested that the procedure can be reversed; i.e., if the spectrum of a radiation device is known, the device can be used as a research tool to search for new isomeric states or to measure as yet undetermined nuclear parameters of known states.

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